Full-Duplex Fiber-Optic RF Subcarrier Transmission Using a Dual-Function Modulator/Photodetector

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***Abstract*—An electroabsorption waveguide device is presented as a dual-function modulator/photodetector for application as a cost-effective full-duplex transceiver in radio-frequency (RF) fiber-optic links. The spectral modulation and detection properties of the dual-function transceiver are characterized experimentally. Extinction ratio, insertion loss, and responsivity are 12 dB, 7 dB, and 0.8 A/W, respectively. Modulation and detection bandwidths are both in excess of 17 GHz. By employing a dual-lightwave technique, optimum modulation and detection performance is simultaneously achieved. Furthermore, full-duplex error-free optical transmission of RF subcarrier-multiplexed signals over 10-km nondispersion shifted single-mode fiber is demonstrated and a point-to-multipoint optical ring architecture is proposed.**

***Index Terms*— Optical-fiber communication, optical modulation, photodetector, subcarrier multiplexing, wavelength division multiplexing.**

I. INTRODUCTION

RECENTLY, fiber-optic networks have attracted great interest for the distribution of microwave and millimeter-wave signals over optical fibers and they have been proposed and used as a low-cost and low-loss transmission medium in many applications such as active phased arrays, wireless access systems, or radio-over-fiber systems [1]–[3].

For the successful implementation of fiber-optic links in mass-market applications, a cost-effective infrastructure is strongly required. Considering the architecture of future fiber-optic networks, where a large number of remote base stations (BS's) will be connected to a single central station (CS), the costs of each BS is obviously a critical factor. Consequently, much research has been directed toward reducing the costs by optimizing the BS's, e.g., by replacing the uplink laser transmitter in the BS with an optical intensity modulator in a so-called "looped-back" configuration [4]. This not only reduces total power consumption of the BS, but also simplifies temperature and bias control and, thus, reduces the costs. Even greater cost savings can be accomplished by employing dual-function electrooptic devices in the BS that provide optical modulation, as well as detection functionality and, therefore, allow for bidirectional fiber-optic transmission.

Previously, Wood *et al.* [5] reported on a dual-function vertical Fabry–Perot multiple-quantum-well (MQW) modulator for bidirectional digital fiber-optic transmission and, more recently, Welstrand *et al.* [6] demonstrated a waveguide electroabsorption (EA) device as a modulator/detector element for analog fiber-optic links. However, in both cases, the electrical bias had to be adjusted to achieve either efficient optical modulation or detection. This requires a bias control circuitry at the BS and only allows for half-duplex (bidirectional, but not simultaneously) transmission. Full-duplex optical transmission using an MQW EA waveguide device in a frequency-division-multiplexed fiber-wireless system is reported in [2], [7], and [8].

In this paper, we present a 1.55-μm InGaAsP/InP EA MQW waveguide device as a dual-function modulator/photodetector. This transceiver device is shown to be an attractive solution for full-duplex fiber-optic transmission. For the first time, a *dual-lightwave* approach is used in conjunction with an EA transceiver (EAT) to simultaneously achieve optimum modulation and detection performance. The advantage of using two wavelengths in conjunction with an EAT is experimentally confirmed by a distinct improvement of the RF uplink and downlink insertion loss. Employing the EAT in a looped-back configuration, we demonstrate full-duplex point-to-point fiber-optic transmission of subcarrier-multiplexed (SCM) signals. Furthermore, we propose an extended architecture for a point-to-multipoint fiber-optic ring network.

II. EAT

The dual-function modulator/photodetector investigated in this paper is a high-speed EA waveguide device with a quaternary InGaAsP MQW core designed for polarization insensitive operation at 1.55-μm optical wavelength. The device utilizes the quantum confined Stark effect (QCSE) for high EA changes due to the red shift of the excitonic resonance [9]. To determine the modulation performance of the dual-function device in terms of extinction ratio and insertion loss, optical transmission measurements were performed using a tunable laser diode with 0-dBm output power as the optical source. From these measurements, a maximum extinction ratio and minimum fiber-to-fiber insertion loss of 12 and 7 dB were found, respectively [10]. Polarization dependence of the extinction ratio is less than 0.5 dB and maximum optical input power is in excess of +10 dBm. The frequency response of the dual-function device was characterized for modulation and detection separately. Experimentally, the 3-dB

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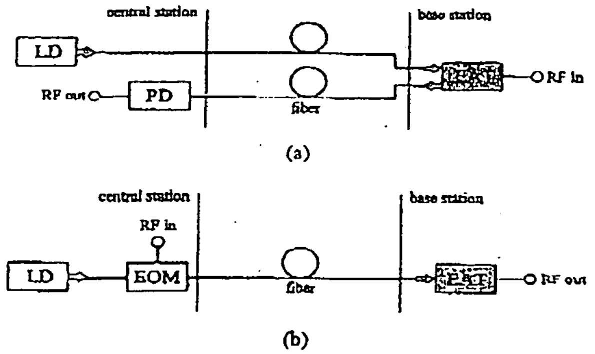

Fig. 1. RF fiber-optic links. (a) Uplink employing an EAT device as an optical modulator in a looped-back configuration. (b) Downlink employing the EAT as a PD.

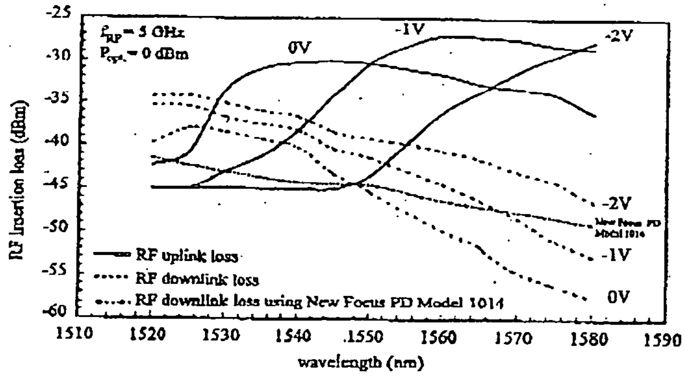

Fig. 2. RF uplink and downlink insertion loss versus optical wavelength at different reverse voltages applied to the EAT.

cutoff frequencies for modulation and photodetection are 17.7 and 17.1 GHz, respectively, [10].

It has been shown in previous work that MQW EA modulators exhibit excellent properties for high-speed analog fiber-optic links [2], [3]. Generally, the optimum performance of an MQW EA modulator is achieved at optical wavelengths approximately 40-60 nm above the excitonic resonance wavelength of the MQW structure [9]. This is because the fundamental absorption of the unbiased modulator is small within this wavelength region and, due to the QCSE, it can be drastically increased by applying a reverse bias. If we intend to use a single MQW waveguide device not only for modulation, but additionally for detection at the same wavelength, a large fundamental absorption is required in order to achieve a high responsivity. This can be accomplished by adjusting the reverse bias of the MQW device for either efficient modulation or efficient photodetection [5], [6]. The drawback of this approach is that it requires the reverse bias of the device to be switched in order to distinguish between modulation and detection performance and, therefore, only half-duplex transmission is possible. Full-duplex transmission can be achieved by operating with an intermediate bias, resulting in a tradeoff between the modulation and detection performance [2], [7], [8]. However, efficient modulation and detection can indeed be simultaneously achieved with a single MQW device by employing a dual-lightwave technique. In this approach, we simultaneously operated the transceiver device with two different wavelengths, one adjusted for optimum modulation while the second wavelength was adjusted for optimum detection performance. The *dual-lightwave* technique enables full-duplex transmission with optimum device performance.

III. Transmission Experiments

For experimental verification, we measured the uplink and downlink radio-frequency (RF) insertion loss of an analog fiber-optic link employing the dual-function EAT device, as illustrated in Fig. 1. These measurements were performed as a function of optical wavelength for different reverse bias applied to the transceiver. Optical input power of the transceiver and RF subcarrier frequency were 0 dBm and 5 GHz, respectively. For comparison, we also measured the downlink RF insertion loss using a commercial InGaAs photodiode (PD) (New Focus, Model 1014) with a specified sensitivity of 0.35 A/W. The measured uplink and downlink RF insertion losses are shown in Fig. 2.

As can be seen, the optimum wavelength for minimum uplink RF insertion loss (solid lines) strongly depends on the applied reverse bias, e.g., at −1-V bias, a minimum uplink RF insertion loss of −28 dB is achieved at 1560-nm wavelength.

The dependence of the uplink RF insertion loss on the optical wavelength and the applied reverse bias is due to a tradeoff between transmission loss, on the one hand, and modulation index, on the other hand. For smaller wavelengths, the uplink insertion loss is increased because of a larger transmission loss whereas, at larger wavelengths, it is increased due to a reduced modulation index. In contrast, the optimum wavelength for minimum downlink RF insertion loss (doted lines) is almost independent of the applied reverse bias. Experimentally, a minimum downlink RF insertion loss of −34 dB is achieved at a wavelength of 1525 nm and −2-V reverse bias.

Fig. 2 clearly demonstrates the advantage of employing the dual-lightwave technique in conjunction with the transceiver. By way of comparison, if the EAT is operated at one particular wavelength, e.g., 1550 nm and −1-V reverse bias instead of using two wavelengths (1525 nm for downlink and 1560 nm for uplink transmission), the uplink insertion loss is increased by 3.5 dB and the downlink insertion loss even by 6.5 dB.

From Fig. 2, we determined the detection responsivity of the transceiver by comparing the downlink RF insertion loss of the transceiver with the RF insertion loss achieved when a PD with a specified responsivity of 0.35 A/W @ 1525 nm is used (dashed line) instead of the transceiver. As can be seen, at 1525 nm and −1-V reverse bias, the RF insertion loss of the fiber-optic link employing the EAT is reduced by 7 dB, as compared to the link employing the InGaAs PD. Thus, the transceiver exhibits a remarkable responsivity of 0.8 A/W.

To demonstrate full-duplex transmission, we performed bit error rate (BER) measurements, using the setup shown in Fig. 3. We used $\lambda = 1525$ nm (LD_1) for the downlink and $\lambda_2 = 1560$ nm (LD_2) for the uplink transmission. Both laser diodes are located within the CS, thus removing the need for a laser diode at the remote BS. For downlink transmission, a 256-Mb/s PRBS ($2^{23} - 1$) was up-converted with a 10-GHz subcarrier frequency. The resulting RF signal was converted into the optical domain using a 20-GHz $LiNbO_3$ modulator,

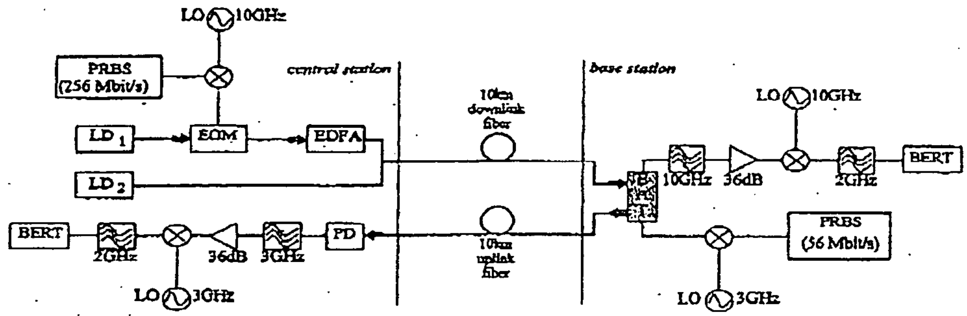

Fig. 3. Experimental setup for full-duplex analog RF fiber-optic transmission of a 256-Mb/s PRBS (downlink) and 56 Mb/s PRBS (uplink) signal. Frequencie used for uplink and downlink subcarrier were 3 and 10 GHz, respectively.

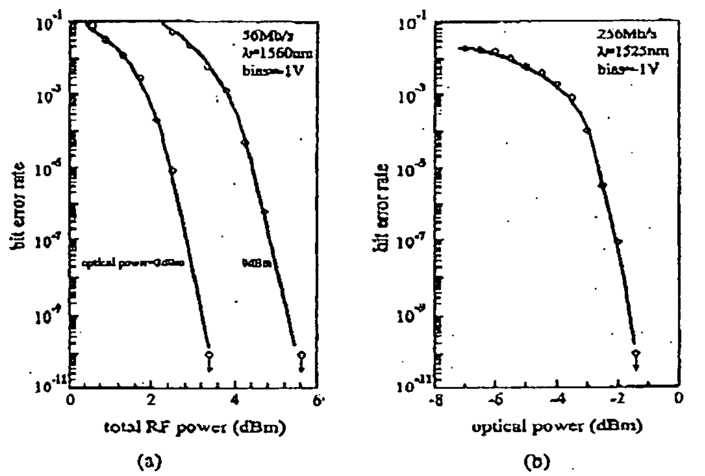

Fig. 4. Measured (a) uplink and (b) downlink BER's for full-duplex transmission. Downlink BER is shown versus optical input power of the EAT device. The uplink BER was characterized as a function of total RF power (carrier and data) applied to the transceiver for different optical input power. Measurement points at BER $= 10^{-10}$ indicate error-free transmission within the measurement times (5 min @ 56 Mb/s and 1 min @ 256 Mb/s).

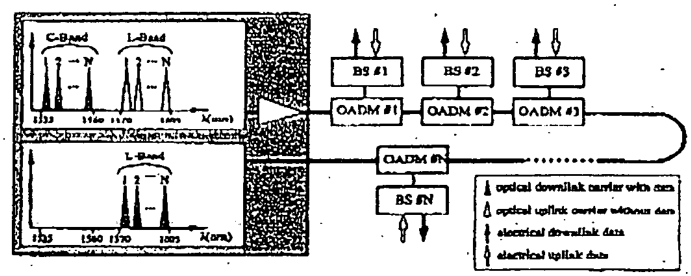

Fig. 5. Proposed architecture for optical point-to-multipoint ring networ with cascaded OADM and BS employing EAT.

and it was transmitted to the BS over 10 km of nondispersion shifted single-mode fiber (NDSF). At the BS, the downlink RF signal was detected by the dual-function transceiver device. For uplink transmission, a 56-Mb/s PRBS ($2^{23} - 1$) was up-converted using a RF carrier frequency of 3 GHz. The up-converted uplink data was coupled to a second transceiver port in order to modulate the optical uplink carrier λ_2. After uplink transmission through the 10-km NDSF, the optical uplink carrier was detected in the CS using an InGaAs PD. No optical amplification was used in the uplink. Both RF signals for uplink and downlink were amplified and down-converted to the baseband in the CS and BS, respectively, and connected to a BER tester (BERT).

The uplink BER versus total RF power (signal and carrier) is shown in Fig. 4(a) for 0- and 3-dBm optical input power to the EAT. In Fig. 4(b), the BER for the downlink transmission using a 256-Mb/s pseudorandom bit sequence (PRBS) is plotted against the optical input power of the transceiver device. As can be seen, full-duplex data transmission at a BER $= 10^{-10}$ was achieved and no error floor was observed.

It should be noted that the local oscillator (LO) frequencies and the maximum bit rates used in the above experiments where given by the center frequencies and the frequency bands of the available RF bandpass filters. More practical subcarrier frequencies for radio-over-fiber systems (i.e., smaller frequency difference), as well as larger bit rates can b envisaged by using different RF bandpass filters. Although up link–downlink mixing is almost completely suppressed in th uplink, the current transceiver design requires different subcar rier frequencies for the uplink and downlink signals becaus of interchannel interference in the EAT module. This remain a drawback, especially for the downlink transmission in mul tichannel SCM links. However, this problem can be circum vented by using an optimized two-section transceiver device

The above transmission experiments have shown that th EAT device in a looped-back configuration in conjunctio with a dual-lightwave technique is an excellent approach fc full-duplex RF subcarrier fiber-optic transmission. At first, th number of necessary optoelectronic components in the BS i reduced to just one transceiver device. Additionally, the R insertion loss of the EAT is comparable or even better tha those of a conventional laser-detector arrangements. In tha respect, we would like to point out that RF insertion los measurements were performed at a moderate optical inpu power of 0 dBm. At larger optical input power, we can expec even lower RF insertion losses than already achieved.

IV. Point-to-Multipoint Wavelength-Divison-Multiplexing Ring Network

The presented optical point-to-point link concept employin an EAT in conjunction with two wavelengths can be extende to point-to-multipoint ring networks, as shown in Fig. 5.

The proposed network architecture consists of a CS an an optical ring backbone connecting the cascaded optic add/drop multiplexer (OADM) and BS with each BS contai ing a single EAT device. Since optimum wavelength separatio between the uplink and downlink channel was found to b

about 35–40 nm (see Fig. 2), we use the optical C-band (1525–1565 nm) for the downlink carrier and the optical L-band (1570–1610 nm) for the uplink carrier. Each C-band carrier is intensity modulated by the downlink data in the CS and multiplexed together with all L-band continuous (CW) carriers. An ultrawide-band Erbium-doped fiber amplifier (EDFA) is used to simultaneously amplify all channels. OADM's containing two fiber Bragg gratings in series are employed to drop the desired optical uplink and downlink carrier to the dedicated BS, where the uplink carrier is being modulated with the uplink data. After the optical uplink carrier is added back into the fiber ring backbone by the OADM, it is transmitted to the CS where the uplink data is recovered.

The proposed network architecture offers a practical solution for point-to-multipoint fiber-optic networks. It is of advantage since all required light sources are centralized in the CS, thus removing the need for laser diodes at the remote BS. Therefore, it allows for a simple BS configuration consisting of a single EAT device.

V. Conclusion

In summary, we experimentally determined the modulation and detection properties of a dual-function EA waveguide device. By employing a dual-lightwave technique, we drastically improved the uplink and downlink RF insertion loss of an analog fiber-optic link by 3.5 and 6.5 dB, respectively. We demonstrated error-free (BER $< 10^{-9}$) and full-duplex transmission of a 256-Mb/s downlink nonreturn to zero (NRZ) ($2^{23}-1$) data stream and a 56-Mb/s uplink NRZ ($2^{23}-1$) data stream and, furthermore, we proposed an extended point-to-multipoint network architecture.

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